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A Miocene (8–12 Ma) intermediate water benthic stable isotope record from the northeastern Atlantic, ODP Site 982

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[1] Oxygen and carbon isotope records are presented for the benthic foraminifer *Cibicidoides wuellerstorfi* from upper middle through lower upper Miocene (11.6–8.2 Ma) sediments recovered at intermediate water depth (1134 m) at Ocean Drilling Program Site 982 on Rockall Plateau. Oxygen isotopic values generally lighter than those for the Holocene indicate significantly warmer intermediate waters and/or less global ice volume during the late middle to early late Miocene than at the present. The most depleted oxygen isotope values occurred at around 10.5 Ma. After this time a long-term increase in δ^{18}O suggests a gradual increase in global ice volume and/or cooling of intermediate waters during the late Miocene. Comparison of the intermediate depth benthic foraminiferal carbon isotope record from Site 982 and records from various North Atlantic deep sites shows that intermediate waters were generally better ventilated than deep waters between 11.6 and 9.6 Ma. During this time period, increased ventilation of intermediate waters was linked to cooling or the build up of polar ice caps. The Mi events originally proposed by *Miller et al.* [1991b] and *Wright and Miller* [1992] are difficult to identify with certainty in sediments sampled at high resolution (<10^4 year). Comparison of the high-resolution benthic δ^{18}O records from ODP Site 982 with the low-resolution benthic δ^{18}O record from Monte Gibliscemi (Mediterranean) show that Mi events, if real, may not be of importance as a stratigraphic tool in upper Miocene sedimentary sequences. *INDEX TERMS:* 1040 Geochemistry: Isotopic composition/chemistry; 4267 Oceanography: General: Paleoceanography; 4870 Oceanography: Biological and Chemical: Stable isotopes; *KEYWORDS:* Paleoceanography, North Atlantic Ocean, Leg 162, ODP Site 982

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1. Introduction

[2] The physical oceanography of the North Atlantic is dominated by the southward spreading of North Atlantic Deep Water (NADW). Seasonal cooling of surface waters results in downwelling of cold and dense waters forming important loci of deep water production in the Nordic Seas. Deep water formed in the Nordic Seas flows over the Iceland-Scotland Ridge, the Wyville-Thompson Ridge and through the Denmark Strait and joins deep water from the Labrador Sea to form NADW. A compensatory flow of upper layer water from the ocean's warm water thermocline feeds NADW production and is a major source of heat to the North Atlantic and surrounding areas [e.g., *Gordon*, 1986].

[3] Carbon isotope (δ^{13}C) values of benthic foraminifers from deep sea cores provide an important tool for the reconstruction of intermediate to deep circulation. The distribution of δ^{13}C is correlated to that of nutrients in the modern ocean [e.g., *Kroopnick*, 1985; *Boyle*, 1988]. Low-δ^{13}C organic matter formed in surface water is oxidized and remineralized in the deep sea, leaving high δ^{13}C values in nutrient-poor surface waters and lowering δ^{13}C values in deep, nutrient-rich waters. In the modern ocean, NADW can be distinguished from other deep water masses by its low nutrient content and relatively high δ^{13}C values, as a result of its formation from nutrient-poor surface waters [e.g., *Broecker and Peng*, 1985]. North Atlantic Deep Water can be divided into two layers: Labrador Seawater (LSW or Upper North Atlantic Deep Water, UNADW) (3–4°C) and Lower North Atlantic Deep Water (LNADW) (1.8–3°C) [*Schmitz and McCartney*, 1993]. The former, LSW, forms the densest intermediate water mass present in the North Atlantic.

[4] Studies of δ^{13}C values of benthic foraminifers from Plio-Pleistocene sections of deep sea cores have shown that during glacials, the production of LNADW was reduced and that production of UNADW or Glacial North Atlantic Intermediate Water (GNAIW) was enhanced [e.g., *Oppo and Fairbanks*, 1987; *Duplessy et al.*, 1988, 1989; *deMenocal et al.*, 1992; *Labeyrie et al.*, 1992; *Oppo and Lehman*,

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1993; *Bertram et al.*, 1995; *Oppo et al.*, 1995; *McIntyre et al.*, 1999; *Venz et al.*, 1999; *Flower et al.*, 2000]. The intermediate depth North Atlantic was filled with a high $\delta^{13}C$ water mass (down to about 2000 m) during Pleistocene glacials, while the deep water mass present below 2000 m water depth during glacials was relatively nutrient-rich and had similar characteristics to that of modern Antarctic Bottom Water today.

[5] During the last glacial maximum, for example, surface circulation in the North Atlantic changed, restricting the transport of warm, saline surface waters to the northern North Atlantic and forcing areas of convection to move further south [*Robinson et al.*, 1995]. The cooler glacial temperatures reduced rates of evaporation, further lowering surface salinities [*Boyle and Keigwin*, 1987; *Duplessy et al.*, 1988]. With a density insufficient to let the water mass sink and form deep water, GNAIW was produced instead.

[6] The Miocene history of North Atlantic intermediate to deep water variability is less well known compared to the Plio-Pleistocene. There has been much debate in past literature about the onset and production history of NADW. Several workers have suggested that Northern Component Water (NCW)/NADW production initiated during the middle Miocene [e.g., *Schnitker*, 1980; *Woodruff and Savin*, 1989, 1991]. However, *Miller and Fairbanks* [1985] have suggested, based on the presence of North Atlantic drift deposits, that NCW/NADW was produced as early as the Oligocene. *Wright and Miller* [1993] also presented isotopic evidence for a pulse of NCW/NADW production during the earliest Oligocene. *Wei and Peleo-Alampay* [1997] suggested that the onset of NCW/NADW production started at about 11.5 Ma (according to the timescale of *Cande and Kent* [1995]) and that it was triggered by general climatic cooling rather than subsidence of the Greenland-Scotland Ridge. They based this conclusion on sedimentological and paleontological data from the North Atlantic and Norwegian Sea. Nevertheless, *Wright and Miller* [1996] suggested that sill depths along the Greenland-Scotland Ridge might have controlled the long-term variations in NCW flux during the Neogene. They argued that NCW overflow over the Greenland-Scotland Ridge was sensitive to small changes in ridge depth caused by topographic swells associated with changes in the flux of buoyant material within the Icelandic Hot Spot, and suggested that middle Miocene cooling may have been the result of a low flux of NCW associated with increased mantle plume activity under Iceland and following uplift of the Greenland-Scotland Ridge. For the middle and late Miocene, the results of *Wright et al.* [1991, 1992] suggest that there were pulses of relatively warm NCW between 12.7 and 11.0 Ma, between 10.4 and 10 Ma, and between 8.6 and 7.8 Ma. The NCW flux was low between 10 and 9.7 Ma (according to the timescale of *Berggren et al.* [1995]). Between 10.9 and 10.6 Ma and between 9.7 and 8.8 Ma, NCW flux estimates are difficult to quantify, due to reduced interbasinal $\delta^{13}C$ differences between the Atlantic and Pacific end-members. In general, however, there seems to have been little to no NCW production between about 9.7 and 8.8 Ma. By 9.4 Ma, all oceans exhibit the same $\delta^{13}C$ values, which implies a shutdown of NCW production and that Southern Component Water (SCW) strongly influenced the North Atlantic [*Wright et al.*, 1991]. These various studies have thus indicated vary dynamic conditions though many uncertainties remain; therefore a dedicated investigation of this period is clearly warranted.

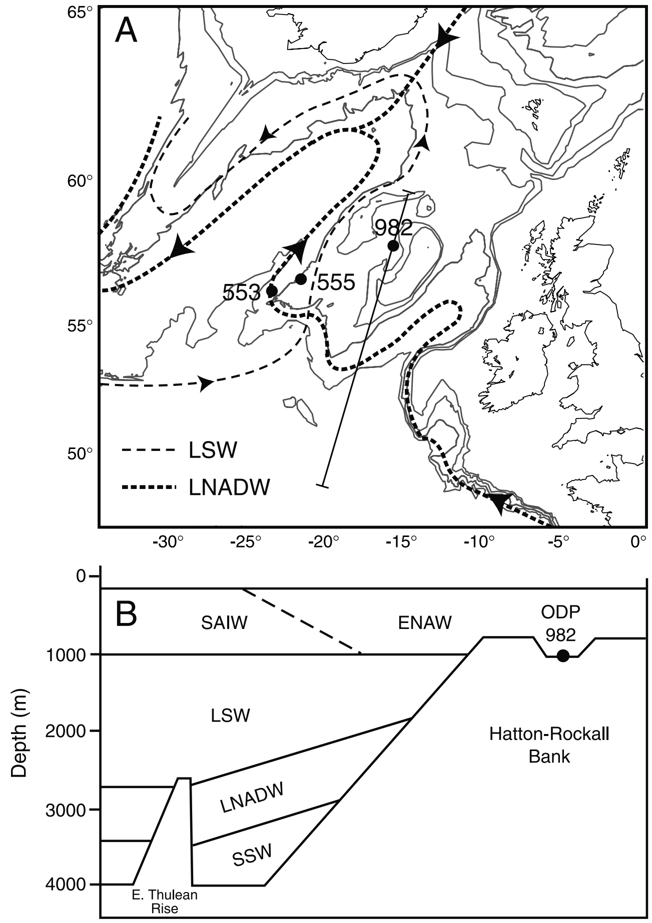

Figure 1. (a) Present paths of major deep water currents in the Rockall area [after *McCave et al.*, 1995]. The locations of ODP Site 982 and DSDP Sites 555 and 553 are shown. Solid black line crossing the Rockall Plateau approximately north–south indicates the position of cross section in Figure 1b. (b) Schematic cross section showing the modern water mass distribution in the Rockall area [after *McCave et al.*, 1995]. LSW = Labrador Seawater, LNADW = Lower North Atlantic Deep Water; ENAW = Eastern North Atlantic Water; SAIW = Sub-Arctic Intermediate Water, SSW = Southern Source Water. See Table 1 for geographical coordinates and references to sites discussed in this study.

[7] The objective of the present study is to describe changes in North Atlantic intermediate water variability in the late middle and early late Miocene (11.6–8.2 Ma). In contrast to the Plio-Pleistocene, there are relatively few high-resolution ($<10^4$ year) stable isotopic records available anywhere for the period of the Miocene between 12 and 8 Ma. ODP Leg 162 provided new sites for investigating the long-term history of North Atlantic intermediate water masses [*Jansen et al.*, 1996]. The shallowest site, ODP Hole 982B (57°31.00′N, 15°51.99′W) (Figure 1, Table 1)

Table 1. Location and Water Depth of Sites and Stations Discussed in This Study

Site/Station	Latitude	Longitude	Depth, m	Reference
ODP 982	57°31′N	15°52′W	1134	this study
DSDP 555	56°40′N	20°47′W	1659	*Wright et al.* [1991]
DSDP 553	56°06′N	23°32′W	2329	*Wright et al.* [1991]
DSDP 608	42°50′N	23°02′W	3526	*Wright et al.* [1991, 1992]; *Miller et al.* [1987, 1991a]
DSDP 563	33°39′N	43°46′W	3796	*Wright et al.* [1991, 1992]; *Miller and Fairbanks* [1985]

was drilled at a water depth of 1134 m in the Hatton-Rockall Basin and is ideally located to study the behavior of North Atlantic intermediate water. Recently, ODP Site 982 has been used to reconstruct the North Atlantic intermediate water circulation history for the past 1 Myr [*Venz et al.*, 1999; *Flower et al.*, 2000]. In the modern ocean, a limb of LSW flows along the Hatton-Rockall Plateau from the Rockall Channel toward the Iceland Basin (Figure 1a). The upper boundary of LSW is close to a water depth of 1000 m [*Schmitz and McCartney*, 1993]. The water mass overlying LSW is Sub Polar Mode Water (SPMW) [*Schmitz and McCartney*, 1993] or the local variety of SPMW, i.e., Eastern North Atlantic Water (ENAW) [*Harvey*, 1982; *van Aken and Becker*, 1996] (Figure 1b). Today, potential temperatures in the Hatton-Rockall basin at the depth of ODP 982 (~1100 m) are 5–6°C [*McCartney*, 1992] indicating the presence of intermediate water, i.e., ENAW. Here we measure the stable isotope composition in benthic foraminifers to reconstruct how intermediate water circulation varied 11.6–8.2 Ma. We also compare our benthic foraminiferal isotopic data with data from other Atlantic sites (Table 1) to examine differences in intermediate and deep water circulation during the late middle and early late Miocene.

2. Material and Methods

[8] ODP Hole 982 was drilled in the Hatton-Rockall Basin, a depression located in the central region of the Rockall Plateau (Figure 1) [*Jansen et al.*, 1996]. A total of four holes were drilled at this location: three of these, Holes 982A, B and C, form a good composite section down to 255 meters composite depth (mcd). Only one hole, Hole 982B, was drilled deeper into the middle Miocene using the extended core barrel. A distinct boundary divides the drilled sequence into two primary lithological units at 57.4 mbsf (upper Pliocene). The studied interval, 298.84–420.14 mcd, belongs entirely to the deeper Unit II [*Shipboard Scientific Party*, 1996]. The major sediment type of Unit II is foraminiferal bearing nannofossil ooze with minor amounts of clay and biogenic silica. Sedimentological and stable isotope data were generated on averages every 10 cm (N = 863). Based on the calculated middle/late Miocene paleodepths of nearby DSDP Sites 553 and 555 (Figure 1) [*Wright et al.*, 1992], we estimate that the Rockall Plateau (and ODP 982) was approximately 100–150 m shallower, than its present depth, during the middle/late Miocene.

[9] All samples were wet-sieved over a 63-μm sieve and later dry-sieved using a 150-μm sieve. The stable isotope measurements were performed on a Finnigan MAT 251 mass spectrometer at the University of Bergen. Benthic stable oxygen and carbon isotope data were primarily generated from analyses of the epifaunal benthic foraminifer *Cibicidoides wuellerstorfi*, but in a few cases were obtained using mixed *Cibicidoides* spp. from the >150 μm fraction. The δ^{18}O data have not been adjusted for isotopic disequilibrium. The stable isotope analyses were performed using 1–2 specimens of *C. wuellerstorfi* or *Cibicidoides* spp. The analytical data are reported referenced to the Vienna Peedee belemnite (VPDB) standard via NBS 19 [*Coplen*, 1996] and an in-house laboratory standard. The analytical errors for measurements of δ^{18}O and δ^{13}C of carbonate standards are 0.07‰ and 0.06‰, respectively. Stable isotopic data from ODP Site 982 in this paper are available from the World Data Center for Paleoclimatology, 325 Broadway, Boulder,

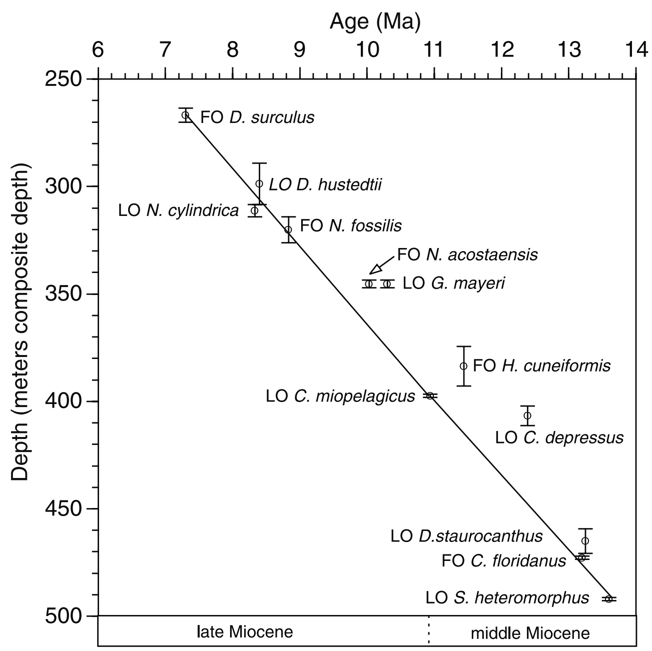

Figure 2. Age-depth relationship for middle and early late Miocene biostratigraphic datums at Site 982. FO first occurrence; LO = last occurrence, *N. fossilis* = *Nitzchia fossilis*, *C. depressus* = *Cannopilus depressus*, *H. cuneiformis* = *Hemidiscus cuneiformis*, *S. heteromorphus* = *Sphenolithus heteromorphus*, *C. floridanus* = *Cyclicargolithus floridanus*, *D. staurocanthus* = *Distephanus staurocanthus*, *D. hustedii* = *Denticulopsis hustedtii*, *N. cylindrica* = *Nitzschia cylindrica*, *C. miopelagicus* = *Coccolithus miopelagicus*, *G. mayeri* = *Globorotalia mayeri*, *N. acostaensis* = *Neogloboquadrina acostaensis*, *D. surculus* = *Discoaster surculus*.

Table 2. Depths and Ages of Mid/Late Miocene Biostratigraphic Control Points at Site 982[a]

Species Event	Age, Ma	Depth Upper, mcd	Depth Lower, mcd	Average Depth, mcd
FO *Discoaster surculus* (N)	7.3	263.53	270.05	266.79
LO *Coccolithus miopelagicus* (N)	10.94	396.69	398.19	397.44
FO *Cyclocargolithus floridanus* (N)	13.2	472.09	473.59	472.87
LO *Sphenolithus heteromorphus* (N)	13.6	491.29	492.79	492.04

[a]Abbreviations are as follows: mcd, meters composite depth; FO, first occurrence; LO, last occurrence; N, calcareous nannofossil.

Colorado; http://www.ngdc.noaa.gov/paleo/paleo.html; email: paleo@ngdc.noaa.gov.

3. Chronology

[10] The age model for the studied interval of ODP Site 982 (Figure 2) was constructed using a slightly modified version of the Leg 162 shipboard biostratigraphic age model. This age model is in agreement with the shipboard age model in the upper part of the studied interval down to the last occurrence (LO) of *Coccolithus miopelagicus*. The age model differs from the shipboard age model in that the average depth and age between the first occurrence (FO) of *Cyclicargolithus floridanus* and the LO of *Sphenolithus heteromorphus*, was chosen as a control point in the middle Miocene (Table 2). The age of the FO of *C. floridanus* (13.20 Ma) is taken from *Raffi and Flores* [1995] rather than the age used on board Leg 162 (Site 982; *Jansen et al.* [1996]). We follow *Berggren et al.* [1995] and use biostratigraphic data that have been correlated to the revised global polarity timescale of *Cande and Kent* [1995]. The sedimentation rates derived with this age model (above and below the LO of *C. miopelagicus* at 397.44 mcd are 3.6 cm/kyr and 3.35 cm/kyr, respectively. With one sample taken every 10 cm, the temporal resolution is one sample every 2.8 to 3.0 kyr. Occasionally, in intervals where benthic foraminifers are rare, the time interval between successive samples is larger, usually twice the initial sampling distance. All data in this study are from Hole 982B. Based on sampling gaps at core breaks, the GRAPE (gamma ray porosity evaluator) record could not be used for further tuning of the age model. The sampling gaps at the core breaks have a duration that vary between 50 and 117 ky, with an average of 78 ky.

4. Results

[11] The benthic oxygen record at ODP Site 982 (Figure 3) exhibits values that are generally lighter than the mean Holocene value (2.2‰) of *Cibicidoides* recorded at the same site [*Venz et al.*, 1999]. The lightest values, as low as 1.3‰, are found at a depth of 10.5 Ma. There are two major long-term trends within the data. First, there is a trend toward

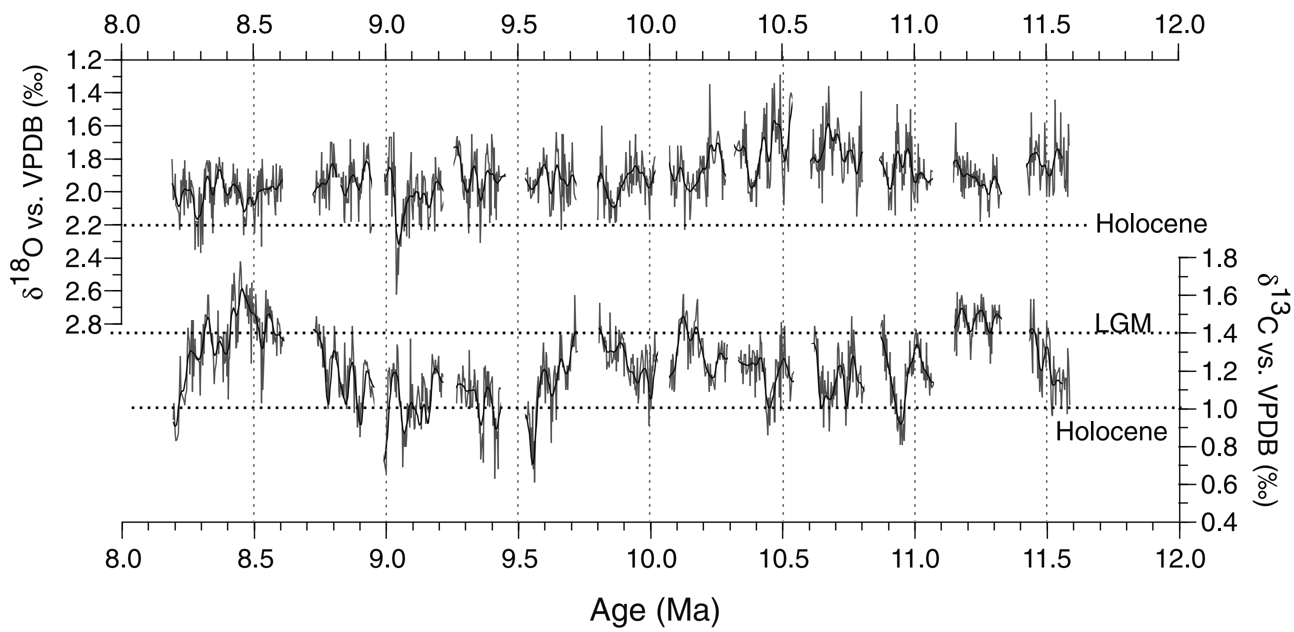

Figure 3. Benthic foraminiferal $\delta^{18}O$ and $\delta^{13}C$ data from Site 982 versus age. Holocene and Last Glacial Maximum (LGM) stable oxygen and carbon isotope mean values (dashed lines) for Site 982 are from *Venz et al.* [1999]. Black solid curve represents smoothed records (50 ky Gaussian window; see *Shackleton and Imbrie* [1990] for description of this smoothing method). Stable oxygen and carbon isotope mean values for the Holocene and Last Glacial Maximum (LGM) for Site 982 are from *Venz et al.* [1999]. All $\delta^{18}O$ values are unadjusted for isotopic disequilibrium.

lighter values from about 11.3–10.5 Ma. This is followed by a general long-term increase in $\delta^{18}O$ from 10.5 Ma to the top of the record, with the most enriched values occurring at 9.05 Ma. Superimposed on these longer trends are high-frequency variations, which have a standard deviation of about 0.17‰. There are several shifts between low and high values in the record, but the amplitude of these events is generally about 0.5‰ and never exceeds 1‰. The amplitude of these Miocene changes can be compared to the Pleistocene benthic glacial-interglacial change of 1.5‰ recorded during MIS 17–24, and the 1.7‰ difference recorded from the Last Glacial Maximum (LGM) to the Holocene in the oxygen isotopic record of ODP Site 982 [*Venz et al.*, 1999]. *Oppo and Lehman* [1993] and *Bertram et al.* [1995] also recorded changes in $\delta^{18}O$ values between the Holocene and LGM of 1.48‰ and 1.60‰ in nearby cores V29-198 and BOFS 17K, respectively. Table 3 summarize the basic statistics of the $\delta^{18}O$ and $\delta^{13}C$ data.

[12] The ODP Site 982 carbon isotope record is marked by several relatively large long-term (10^5 year) fluctuations, that have no counterpart in the oxygen isotope record (Figure 3). Carbon isotopic ratios fluctuate over a total range of approximately 1.2‰. The majority of the data fluctuate between the mean Holocene (1.0‰) and LGM (1.4‰) values measured for ODP Site 982 [*Venz et al.*, 1999]. At ODP Site 982, the difference in $\delta^{13}C$ between the Holocene and LGM is 0.4‰, slightly lower than the corresponding difference of 0.47‰ measured in cores V29-198 [*Oppo and Lehman*, 1993] and BOFS 17K [*Bertram et al.*, 1995].

[13] On a longer timescale (10^6 years), the carbon and oxygen isotope records from ODP Site 982 show little covariance. Whereas the long-term trend in the oxygen isotope record indicates a steady increase in $\delta^{18}O$ after about 10.5 Ma, the carbon isotope record displays greater variability over this interval (Figure 3). Only in the oldest part of the studied sequence (i.e., prior to ~10 Ma) do the longer trends in the carbon and oxygen isotope records appear to covary. The apparent decoupling of $\delta^{18}O$ and $\delta^{13}C$ over longer timescales after 10 Ma suggests that intermediate water production (as inferred from $\delta^{13}C$) did not vary linearly with ice volume (as measured from $\delta^{18}O$) during this time period.

[14] If we look at the higher frequency fluctuations in the oxygen and carbon isotope records, we find a relationship that could be analogous to the glacial-interglacial circulation changes that the Atlantic experienced during the Plio-Pleistocene. There is a positive correlation between $\delta^{18}O$ and $\delta^{13}C$ values (Table 4) from 11.6 to 9.9 Ma, in particular between 11 and 10 Ma (Figure 3). Dividing the record younger than 9.9 Ma into two intervals (9.9–9.0 Ma and 9.0–8.2 Ma) we see that the correlation is weaker (9.0–8.2 Ma) or slightly negative (9.9–9.0 Ma). Table 4 summarizes the results from the correlation between $\delta^{13}C$ and $\delta^{18}O$ records from ODP Site 982.

Table 3. Summary of $\delta^{18}O$ and $\delta^{13}C$ Data

Statistics	$\delta^{18}O$, ‰	$\delta^{13}C$, ‰
Mean	1.91	1.23
Maximum	2.62	1.78
Minimum	1.29	0.61
Standard deviation	0.17	0.19

Table 4. Pearson's Correlation Coefficient for $\delta^{13}C$ Versus $\delta^{18}O$ Data From ODP Site 982[a]

Interval, Ma	Pearson's r	95% Confidence Interval
11.6–9.9	0.33	0.41 to 0.24
9.9–9.0	−0.14	−0.02 to −0.27
9.0–8.2	0.06	0.19 to −0.07

[a]Note that the stable isotope data were slightly smoothed before the correlation was performed.

5. Discussion

5.1. ODP Site 982 $\delta^{18}O$ and $\delta^{13}C$ Records

[15] The positive covariance between carbon and oxygen isotope fluctuations in the older half of the record indicate that the ventilation of intermediate water masses increased during periods of warmer climates and/or less ice volume, and vice versa. The high $\delta^{13}C$ values during periods of inferred cooling (high $\delta^{18}O$ values) suggest that there could have been shifts in the vertical nutrient distribution between intermediate and deep waters between glacials and interglacials similar to those that occurred during the Pleistocene, even during times when the overall global climate was warmer than today's. Evidence suggesting cooler conditions between 11.5 and 11.0 Ma is present in sediments from ODP Sites 642 and 644 in the Norwegian Sea (Vøring Plateau). At these sites, ice-rafted debris (IRD) is present as early as 12.5 Ma [*Fronval and Jansen*, 1996]. Between 11.5 and 11.0 Ma, IRD was recorded more frequently relative to the rest of the middle and lower upper Miocene record. However, the number of IRD grains per gram of sediment is low and provides little evidence of changes in the strength or extent of the assumed glacial events causing the IRD to accumulate in the Norwegian Sea.

5.2. Comparisons of ODP Site 982 With Northeast Atlantic and Global Composite Deep Water Records

[16] Before we turn to comparisons between ODP Site 982 and other North Atlantic deep water records, we first look at the pattern of intermediate and deep water circulation at the Rockall Plateau through the late middle and early late Miocene. Figure 4 shows the carbon and oxygen isotopic records of ODP Site 982 (this study), DSDP Site 555 (1659 meter water depth) and DSDP Site 553 (2329 meters water depth) [*Wright et al.*, 1991] (Table 1). In the modern ocean, ODP Site 982 is bathed by ENAW, while DSDP Sites 555 and 553 are located at depth bathed by LSW and LNADW, respectively (Figure 1). Based on carbon isotope data (Figure 4), the water masses bathing Site 982 and the slightly deeper Site 555 seem to be relatively similar. However, this interpretation should be taken with caution due to the irregular sampling of DSDP Site 555. The $\delta^{13}C$ values of DSDP Site 553, on the other hand, were generally more depleted prior to about 9.6 Ma than ODP Site 982, and possibly also relative to DSDP Site 555. This suggests lower nutrient content of the water mass bathing Site 982 compared to water masses at deeper depth. At about 9.7, Ma there is a marked decrease in $\delta^{13}C$ in the

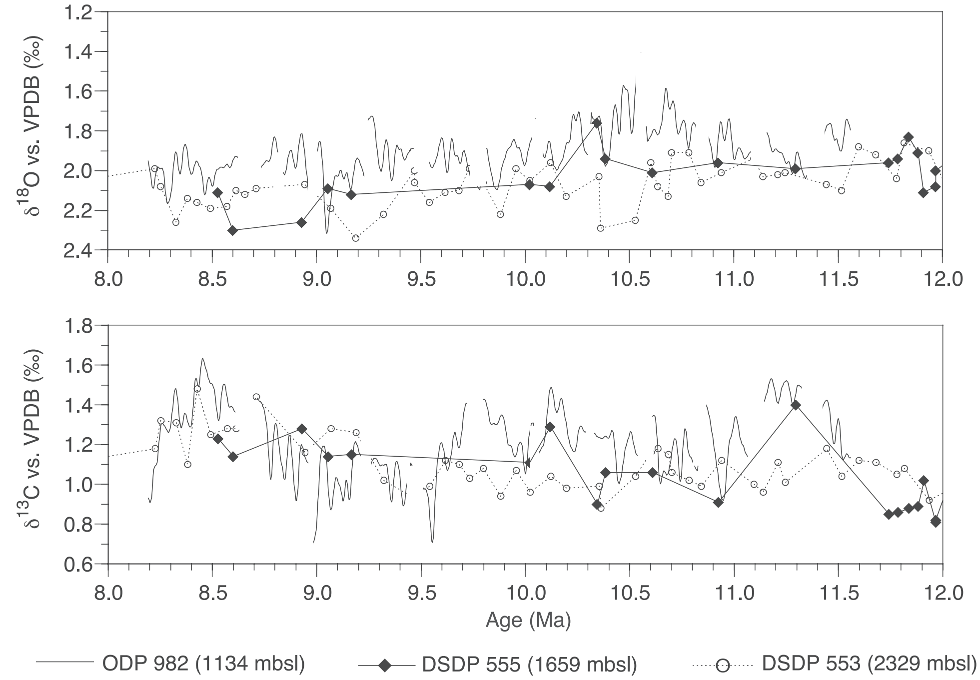

Figure 4. Benthic foraminiferal $\delta^{18}O$ and $\delta^{13}C$ data from ODP 982 and DSDP Sites 555 and 553 (Rockall Plateau). Data from DSDP Sites 553 and 555 are from *Wright et al.* [1991], with ages updated to *Berggren et al.* [1995] for Site 553 by *Zachos et al.* [2001] and for Site 555 by this study. The record from ODP Site 982 has been smoothed using a Gaussian window of 50 ky.

carbon isotopic record of ODP Site 982, indicating a considerable decrease in ventilated of intermediate waters. From about 9.6, Ma all three records display similar $\delta^{13}C$ values and the same longer trend in increasing $\delta^{13}C$ values. In the more highly resolved $\delta^{13}C$ record from ODP Site 982, this trend is interrupted by several low-$\delta^{13}C$ events.

[17] The oxygen isotope record from ODP Site 982 is generally lighter than the oxygen isotope records from DSDP Sites 555 and 553 throughout the studied interval (Figure 4). Due to the low resolution and somewhat irregular sampling of DSDP Site 555 and 553 relative to Site 982, it is difficult to evaluate the origin of this difference. Today, ENAW is slightly warmer but also more saline than LSW, which makes it difficult to explain the difference of occasionally close to 1‰ in $\delta^{18}O$ or more. One explanation could be that the temperature gradient between intermediate and deeper waters was larger during the studied time period than today.

[18] At ODP Site 982, the period 11.5–11.0 Ma corresponds to an interval of higher $\delta^{18}O$ values than the interval 10.8–10.4 Ma (Figures 3 and 4), suggesting relatively cooler conditions in the subpolar North Atlantic during this time. The lighter $\delta^{13}C$ values recorded by deeper DSDP Site 553 (2923 m) relative to Site 982 (Figure 5) suggest that intermediate waters at the depth of Site 982 were relatively more ventilated during this time. In contrast, between 10.8 and 10.4 Ma, when the lightest $\delta^{18}O$ values are recorded at ODP Site 982, $\delta^{13}C$ values at this site are lighter than 11.5–11.0 Ma, while the deeper Site 553 records a slight increase in $\delta^{13}C$. Despite the low resolution of the Site 553 record, it seems like there is an increase in ventilation of intermediate waters and a decrease in ventilation of deeper waters during intervals of higher $\delta^{18}O$.

[19] DSDP Sites 608 and 563 (Figure 1, Table 1) (at 3526 and 3796 meter water depth, respectively) [*Miller and Fairbanks*, 1985; *Miller et al.*, 1987, 1991a; *Wright et al.*, 1991, 1992] provide the means for a more regional comparison between intermediate and deep water records during the late middle and early late Miocene in the North Atlantic (Figure 5). Today, DSDP Site 563 is influenced by a water mass composed of 87% NCW and 13% SCW, while DSDP Site 608 is bathed by a mixture of 91% NCW and 9% SCW [*Wright et al.*, 1991]. GEOSECS data (stations 29 and 30), situated close to DSDP Site 563, show a modern bottom $\delta^{13}C$ value of about 1‰, the same as for NADW.

[20] A comparison of data between ODP Site 982 and DSDP Sites 563 and 608 (Figure 5) points toward well-ventilated intermediate waters at ODP Site 982 during most of the period between 11.6 and 9.6 Ma, whereas the deep sites (Figure 6) were largely bathed by a lower $\delta^{13}C$-rich water mass. An exception to this is the period 10.1–9.9 Ma, during which the three sites exhibit similar $\delta^{13}C$ values. The relative nutrient-enrichment inferred from the low $\delta^{13}C$ values at the deep water sites from 11.8 to 9.6 Ma is more pronounced at Site 608 than at Site 563. If it were a southern source water mass affecting the deeper parts of the North Atlantic during this time, one would perhaps expect the deeper Site 563 to be more strongly influenced. However, *Miller et al.* [1987] also noted a depletion of the carbon isotopic record from Site 608 relative to Site 563 in the early Miocene and proposed isolation and reduced ventilation of the Kings Trough area (DSDP Site 608)

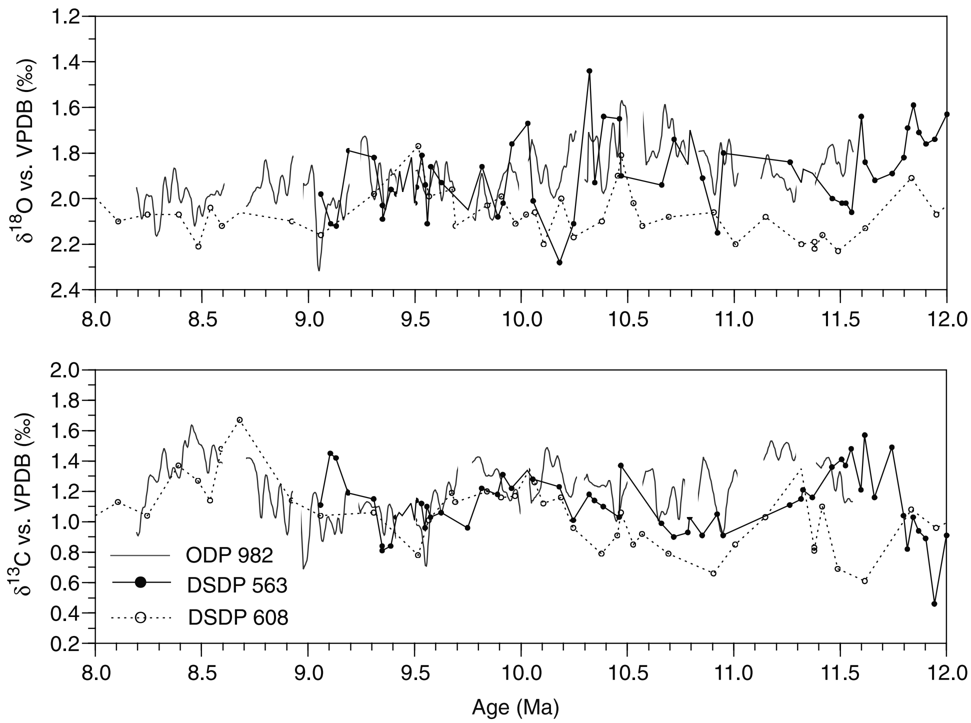

Figure 5. Benthic foraminiferal $\delta^{18}O$ and $\delta^{13}C$ data from ODP 982, and DSDP Sites 563 and 608. Data from DSDP Sites 563 and 608 are from *Miller and Fairbanks* [1985]; *Miller et al.* [1987, 1991a]; *Wright et al.* [1991, 1992] with ages updated to *Berggren et al.* [1995] by *Zachos et al.* [2001]. The record from ODP Site 982 has been smoothed using a Gaussian window of 50 ky.

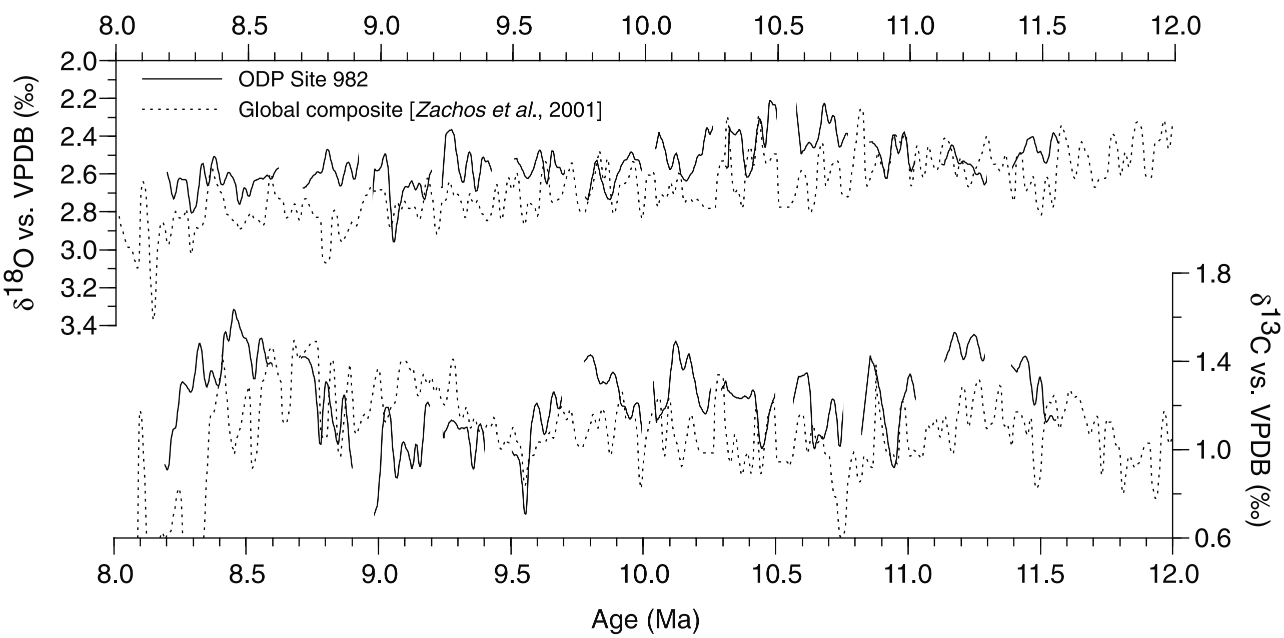

Figure 6. Comparison between the long-term trends in the stable oxygen and carbon records from ODP Site 982 (solid line), and the global deep sea composite of *Zachos et al.* [2001]. Both records have been smoothed using a 50 ky Gaussian window. The smoothing method used in this study differs from the one used by *Zachos et al.* [2001]; however, the degree of smoothing applied here results in roughly the same degree of smoothing as for their global deep-sea composite. To adjust for genus-specific isotope vital effects, the $\delta^{18}O$ values were adjusted by +0.64‰ (*Cibicidoides*) and +0.4‰ (*Nuttallides*) [*Shackleton et al.*, 1984; *Shackleton and Hall*, 1997].

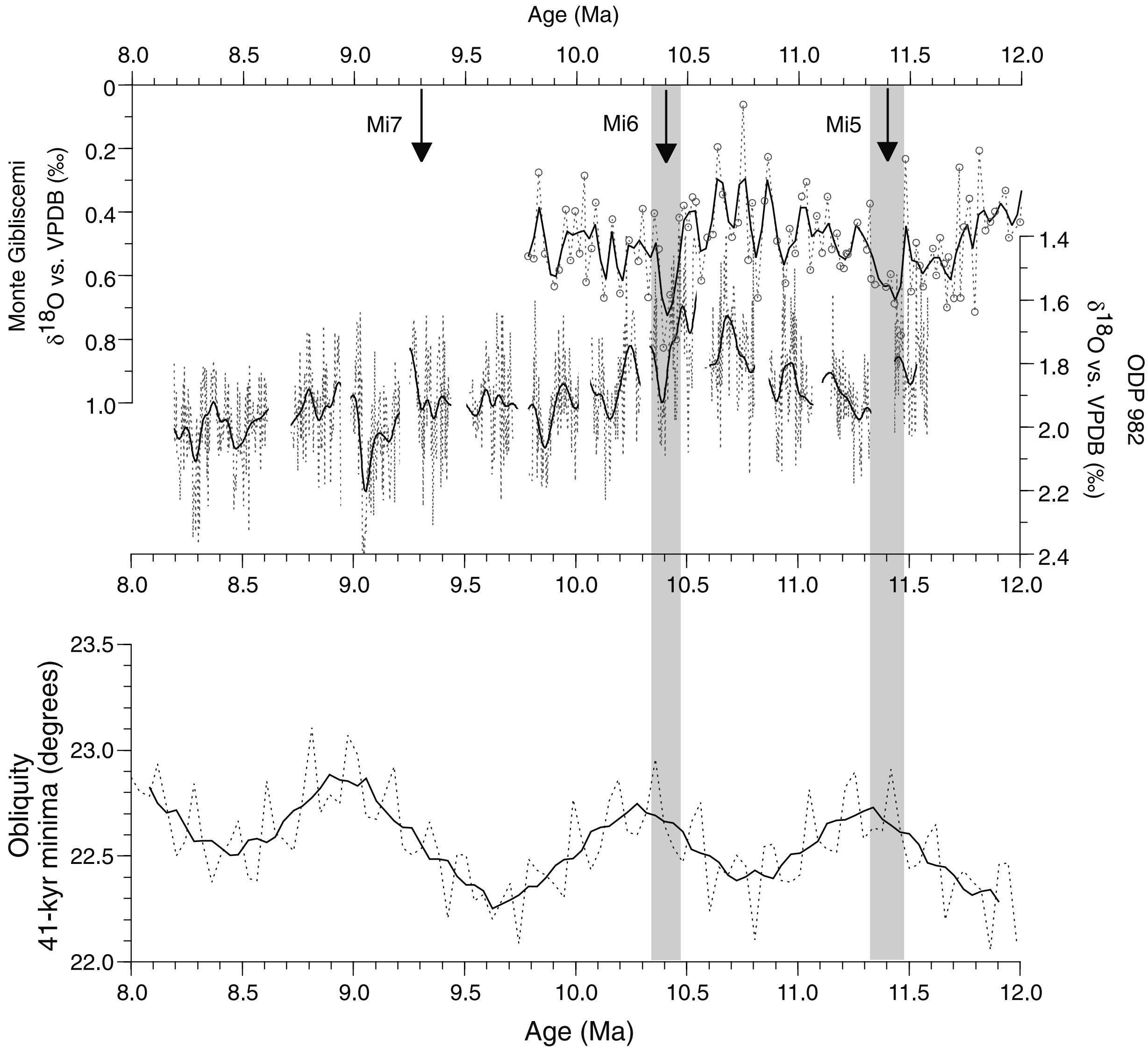

Figure 7. (top) Comparison between the benthic oxygen isotope records from ODP Site 982 (this study) and Monte Gibliscemi [*Turco et al.*, 2001]. Both records have been smoothed (solid lines) using a 100 ky Gaussian window. Arrows indicate the astronomically ages for Mi5 and Mi6 [*Turco et al.*, 2001]. The age for Mi7 is not astronomically calibrated, but simply updated to the timescale of *Berggren et al.* [1995]. (bottom) Stippled line connects successive obliquity minima, solid line corresponds to the 5-point moving average of this time [after *Turco et al.*, 2001].

during this interval. Isolation and reduced ventilation of the Kings Trough area may help to explain the periodically depleted $\delta^{13}C$ values at DSDP Site 608 prior to 10.25 Ma (Figure 5). However, Figure 7 also shows a comparison between the oxygen isotope records from Site 982 and Sites 563 and 608. Both the major trends as well as the absolute $\delta^{18}O$ values recorded at Site 982 and Site 563 are generally similar throughout most of the record. In contrast, DSDP Site 608 is generally also more enriched in ^{18}O than DSDP Site 563 between 12 and 9.9 Ma. This could suggest differences in bottom water temperature and/or seawater $\delta^{18}O$ between basins. If ascribed entirely to temperature differences, these data indicates that the eastern North Atlantic (DSDP Site 608) was about 1–2°C cooler than the western basin (DSDP Site 563). These findings are difficult to explain in terms of modern North Atlantic oceanographic settings and may indicate that circulation patterns in the eastern and western basins were different during the late middle Miocene. In conclusion, the $\delta^{13}C$ comparison between intermediate and deep waters site at the Rockall area suggested the presence of better-ventilated intermediate waters relative to deep waters between 11.6 and 11.0 Ma. However, the limited data available for DSDP Sites 563 and 608 are highly variable between 11.6 and 11.0 Ma and difficult to interpret.

[21] By comparing the oxygen and carbon isotope records from ODP Site 982 with the most recently published global isotope composite record [*Zachos et al.*, 2001], we may

evaluate the trends at Site 982 in a global context. Figure 6 shows the benthic $\delta^{18}O$ record from ODP Site 982 compared with the global deep sea $\delta^{18}O$ composite by *Zachos et al.* [2001]. It is clear from Figure 6 that the long-term trend of increasing $\delta^{18}O$ values at ODP Site 982 from 10.5 to 8.2 Ma seems to mirror the global trend to a great extent. This increase corresponds to gradual cooling and small-scale ice sheet expansion on Antarctica [*Zachos et al.*, 2001]. At Site 982, the magnitude of this long-term increase, from the lightest value recorded at 10.5 Ma to the youngest values at around 8.2 Ma, is about 0.4‰. In the global deep sea composite, the increase is about the same (0.5‰). A peak-to-peak comparison between the ODP Site 982 and the global deep sea composite could suggests a 200–250 ky offset between the two records (Figure 6). The low $\delta^{18}O$ values at ODP Site 982 around 10.5–10.6 Ma possibly correspond to a low $\delta^{18}O$ values in the global deep sea composite at 10.3–10.4. Similarly, a peak of high $\delta^{18}O$ values at Site 982 centered at 9.05 Ma could correspond to high $\delta^{18}O$ values in the global deep sea composite at 8.8 Ma. The age of the younger of these two events is better constrained than the older event. Between about 9 and 13 Ma, the age-model of Site 982 is largely governed by only one age-control point (the LO of *C. miopelagicus*, Figure 2), which leaves room for alternative interpretations of the age-depth model of this site.

[22] The carbon isotope values at ODP Site 982 are on average enriched by about 0.2‰ relative to the global deep sea $\delta^{13}C$ composite between 11.6 and 9.6 Ma (Figure 6), indicating well-ventilated intermediate waters in the northeastern Atlantic and/or the influence of comparatively nutrient-rich waters at greater depth in the deep sea during this period. Between 9.7–9.5 Ma, a convergence between $\delta^{13}C$ values of intermediate waters and deep waters suggests a reduction in intermediate water production at this time. By 8.7 Ma, the $\delta^{13}C$ values of the average deep ocean again becomes depleted compared to intermediate waters in the northeast Atlantic, implying reduced ventilation deeper in the water column.

[23] The results from these $\delta^{13}C$ comparisons lead to the same conclusion. From 11.6–9.6 Ma intermediate waters at the depth of Site 982 are inferred to have between nutrient-depleted relative to deep water sites, with the exception of the period between 10.1 and 9.9 Ma (Figures 4, 5, and 6). Between 9.7–9.5 Ma, $\delta^{13}C$ values recorded at Site 982 increase and converge on the $\delta^{13}C$ values recorded at the deeper depths. The deep water records display a long-term increase in $\delta^{13}C$ beginning about 9.5 Ma at the North Atlantic sites, but closer to 9.0 Ma in the global deep sea composite. A similar trend toward higher $\delta^{13}C$ values is also observed at ODP Site 982, albeit interrupted by several short-term excursions toward lighter $\delta^{13}C$ values.

5.3. Miocene Isotopic Events

[24] Comparisons of benthic and low-latitude planktic foraminiferal $\delta^{18}O$ records can be used to separate ice volume effects from more local temperature changes. *Miller et al.* [1991b] and *Wright and Miller* [1992] erected twelve Oligocene to Miocene benthic foraminiferal $\delta^{18}O$ zones based on coeval increases in benthic and low-latitude planktic $\delta^{18}O$ records. The majority of these $\delta^{18}O$ maxima were interpreted to reflect substantial My-scale ice volume increases and deep water cooling. *Lourens and Hilgen* [1997] further suggested a possible correlation between third-order eustatic cycles and cool, glacial episodes (the Mi events) during the late Miocene. Recent results from an astronomically dated deep marine succession in the Mediterranean indicate that the Mi6 and Mi5 events occurred at 11.4 and 10.4 Ma (Figure 7), respectively [*Turco et al.*, 2001]. Furthermore, *Turco et al.* [2001] found that these events of global climate cooling appear to be linked to periods of low-amplitude variations in obliquity (Figure 7), in contrast to the last 5.3 million years when major steps in glacial build-up are related to increasing amplitude variations in obliquity *Lourens and Hilgen* [1997].

[25] Figure 7 shows a comparison between the benthic $\delta^{18}O$ records from Monte Gibliscemi [*Turco et al.*, 2001] and ODP Site 982. A sampling gap between 11.4 and 11.3 Ma in the Site 982 $\delta^{18}O$ record makes it is difficult to accurately evaluate the presence of Mi5 in this record. Nonetheless, there is an increase in $\delta^{18}O$ values recorded between 11.4 and about 11.3 Ma at Site 982 that could correspond to Mi5. There is a marked increase in $\delta^{18}O$ at ODP Site 982 between 10.55 and 10.4 Ma, which correlates reasonably well with Mi6 in the Gibliscemi record (Figure 7). Figure 7 also shows the age of Mi7. This event has not been astronomically calibrated yet and the arrow in Figure 7 represents the age of Mi7 (9.3 Ma) after recalibration to the timescale of *Berggren et al.* [1995]. There is no presence of a marked increase in $\delta^{18}O$ at ODP Site 982 at 9.3 Ma: in contrast, ODP Site 982 displays relatively light $\delta^{18}O$ values at this time. However, a shorter period of markedly higher $\delta^{18}O$ values centered at about 9.05 Ma is present in the Site 982 $\delta^{18}O$ record. That fact that the age-model for ODP Site 982 lacks reliable biostratigraphic age-control point over long periods of time during the late middle and early late Miocene (Figure 2) leaves uncertainties concerning the exact timing of, e.g., the high $\delta^{18}O$ values around 9.05. A 250 ky shift of the Site 982 record toward older ages, would result in a match between Mi7 at Monte Gibliscemi and the marked $\delta^{18}O$ increase at Site 982 around 9.05 Ma. As mentioned above, the 9.05 Ma event at ODP Site 982 could also correspond to an event of increased $\delta^{18}O$ values around 8.8 Ma in the global deep sea composite by *Zachos et al.* [2001]. However, the shift needed in the Site 982 age-model to produce a match between the 8.8 Ma cool event in the global deep sea composite and the Site 982 cool event at 9.05 would in this case be a 250 ky shift toward younger ages. Hence, although the age-depth model for ODP Site 982 is loosely constrained over long periods of time in the middle/late Miocene, the evidence suggesting possible changes to the age-depth model are not consistent.

[26] In summary, it is appears to be difficult to identify with certainty the Mi events originally proposed by *Miller et al.* [1991b] and *Wright and Miller* [1992] in the closely sampled sedimentary sequence at Site 982. Although it is possible that there is a correlation between the increase in $\delta^{18}O$ recorded at about 10.4 Ma in ODP Site 982 that corresponds to Mi6, there are numerous enriched-$\delta^{18}O$

events of similar magnitude throughout this record. So far, most records in which Mi events have been recognized are of relatively low resolution and it is possible that the $\delta^{18}O$ increases recorded during Mi events are the result of aliasing. However, even if these periods of increased $\delta^{18}O$ are globally recorded events of ice build-up and deep water cooling, they seem to get lost in the high-frequency variability of a closely sampled record, such as that from ODP Site 982. We agree with *Shackleton and Hall* [1997], who suggested based on a highly resolved discontinuous deep water benthic $\delta^{18}O$ record from ODP Site 926 (western equatorial Atlantic), that the $\delta^{18}O$ variability observed in upper Miocene sediments is probably not appropriate as a correlation tool. Additional, well-dated high-resolution middle and upper Miocene benthic and low-latitude planktic oxygen isotope records are needed to further evaluate the existence of Mi events, their origin, and their potential as correlation tools for sedimentary sequences.

6. Conclusions

[27] Based on benthic oxygen and carbon isotopic data from the late middle through early late Miocene sequence at ODP Site 982, and comparisons between these data and other published benthic isotopic records, we draw the following conclusions:

1. Oxygen isotopic values generally lighter than the Holocene mean indicate significantly warmer intermediate waters and/or less global ice volume during the late middle to early late Miocene relative to the present. The lightest oxygen isotope values were recorded at around 10.5 Ma, when a long-term increase in foraminiferal $\delta^{18}O$ at ODP Site 982 began that correlates with changes in the global $\delta^{18}O$ deep sea composite of *Zachos et al.* [2001].

2. Comparisons between North Atlantic intermediate (ODP Site 982) and deep water (DSDP Sites 553, 563, 608) carbon isotopic records suggest that intermediate waters were generally better ventilated relative to the deep North Atlantic from 11.6 to 9.6 Ma. Over this time period, there is also evidence pointing toward increased ventilation of intermediate waters relative to the deep Atlantic during intervals of increased $\delta^{18}O$ values, on both longer and shorter timescales.

3. It is appears to be difficult to identify with certainty the Mi events originally proposed by *Miller et al.* [1991b] and *Wright and Miller* [1992] in the densely sampled sequence of Site 982. Comparison of the high-resolution benthic $\delta^{18}O$ record from this site with the lower resolution benthic $\delta^{18}O$ record from Monte Gibliscemi (Mediterranean) shows that Mi events, if real, may not be useful as a stratigraphic tool in upper Miocene sedimentary sequences.

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